(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) Publication number: 0 338 688
A1

(12) EUROPEAN PATENT APPLICATION

(21) Application number: 89303120.3

(51) Int. Cl.4: G01P 15/13 , G01P 15/125

(22) Date of filing: 30.03.89

(30) Priority: 01.04.88 JP 78034/88

(43) Date of publication of application:
25.10.89 Bulletin 89/43

(84) Designated Contracting States:
DE FR GB

(71) Applicant: HITACHI, LTD.
6, Kanda Surugadai 4-chome Chiyoda-ku
Tokyo(JP)

(72) Inventor: Suzuki, Seikou
3705, Kanai-cho
Hitachioota-shi Ibaraki 313(JP)
Inventor: Tsuchitani, Shigeki
1830-17, Kawawada 1-chome
Mito-shi Ibaraki 311-41(JP)
Inventor: Shimada, Satoshi
4-22, Minami Kouya-cho 3-chome
Hitachi-shi Ibaraki 319-12(JP)
Inventor: Miki, Masayuki
2643-1, Katsukura
Katsuta-shi Ibaraki 312(JP)
Inventor: Kobori, Shigeyuki
18, Minami Kouya-cho 3-chome
Hitachi-shi Ibaraki 319-12(JP)
Inventor: Matsumoto, Masahiro
10-12, Suehiro-cho 3-chome
Hitachi-shi Ibaraki 316(JP)

(74) Representative: Molyneaux, Martyn William et al
c/o Ladas & Parry Isartorplatz 5
D-8000 Munich 2(DE)

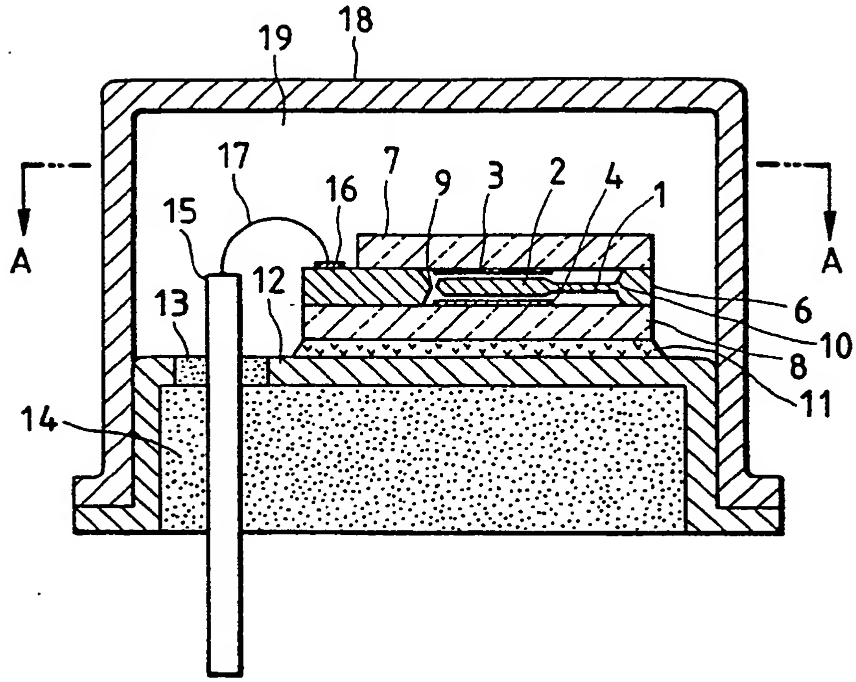
(54) Accelerometer.

(57) An accelerometer having, a movable electrode which is movable according to acceleration, a fixed electrode disposed in opposition to the movable electrode, an output means for generating an output voltage which is proportional to the acceleration by measuring a gap between the movable electrode and the fixed electrode, a pulse width modulation means for generating pulses, wherein a pulse width of the pulses is modulated according to the output voltage, and a feedback means for feeding back an electrostatic force which is proportional to the pulse width of the pulses from the pulse modulation means between the movable electrode and the fixed electrode.

As the acceleration in the acceleration sensor is linearly detected, the acceleration sensor is easily adjusted.

EP 0 338 688 A1

FIG. 5



Accelerometer

Background of the Invention

This invention relates to an accelerometer and more particularly to an accelerometer which will be suitable for a car body control system of a vehicle. Incidentally, an accelerometer capable of accurately detecting the range of 0 ~ ±1(G) and 0 ~ 10(Hz) is required with 1(G) being equal to 9.8(m/s^2).

A large number of systems have been established for accelerometer. Known systems include a piezoelectric system using a piezoelectric effect of a piezoelectric material, a strain gauge system using a piezoresistance effect, a servo system having a force feedback system, a magnetic system utilizing a differential transformer, an optical system utilizing a photo-interrupter, a capacitance system utilizing miniaturization etching technique of silicon, and so forth. Among them, it is believed possible to drive the capacitance type sensor utilizing the miniaturization etching technique of silicon by an electrostatic servo.

The system which drives the capacitance type sensor utilizing the conventional miniaturization etching technique of silicon by the electrostatic servo involves the drawbacks that a compensation circuit for linearizing non-linearity is needed because non-linearity of the electrostatic servo mechanism is great, the output characteristics can not be adjusted easily and the production yield is low.

TRASDUCERS '87, The 4th International Conference Solid-State Sensors and Actuators, Pages 395 to 398 and U.S. Patent No. 4,483,194 are cited as examples of such device.

The typical structure of the electrodes 2 to 4 and cantilever 1 which is generally known is shown in Figure 2(b), and an electrical circuit thereof is shown in Figure 2(a).

A movable electrode 2 serving also as a weight is formed at the tip of a cantilever 1 by etching a silicon plate 6 from both of its surfaces. Fixed electrode 2 are made of a metal such as aluminum and are formed by vapor deposition onto glass plates 7, 8, respectively.

Assuming that capacitances between the movable electrode 2 and the fixed electrodes 3 and 4 are C_1, C_2, respectively, the values of C_1, C_2 are proportional to the displacement of the movable electrode 2, that is, the acceleration α(G). The most typical measurement method of the conventional capacitance type accelerometer detects the acceleration α(G) from the absolute values of the capacitances C_1, C_2 or their difference ΔC. As will be described next, this measurement method involves the problem that the production yield drops because the output characteristics fluctuate greatly due to the variance of the initial gap dimension between the movable electrode 2 and the fixed electrodes 3, 4 that occurs during production.

Fig. 3 shows an example of the relation between the acceleration and the capacitance when the movable electrode 2 undergoes displacement in accordance with the acceleration α(G). The diagram shows the case where the initial gap d_o between the movable electrode 2 and the fixed electrodes 3, 4 is 3 μm. As shown in the drawing, the capacitances C_1, C_2 and their difference ΔC have large non-linearity to the displacement ω of the movable electrode (which is proportional to the acceleration α) and it is difficult to detect highly accurately the acceleration α. Incidentally, the capacitance C between the electrodes is given by the following formula as is well known:

$$C = \frac{\varepsilon_O s}{d} \qquad \cdots\cdots (1)$$

where

ϵ_o: vacuum dielectric constant,

s: area of electrode,

d: gap between electrodes.

Since the capacitance C is inversely proportional to the gap dimension d, non-linearity becomes great as shown in Fig. 3. As can be understood from the formula (1) and Fig. 3, if the initial gap d_o between the movable electrode 2 and the fixed electrodes 3, 4 is greater than 3 μm when the production is complete, sensitivity and non-linearity of the capacitance C_1, C_2 and their difference ΔC with respect to the change of the acceleration α fluctuate greatly. Therefore, when the acceleration α is detected from the capacitance change, the variance of the initial gap dimension at the time of production must be an extremely small

value. In practice, however, these conventional technique has the drawbacks as that the initial gap dimension at the time of production is not constant as shown next.

Summary of the Invention

It is an object of the present invention to provide a capacitance type accelerometer which does not need a non-linearity compensation circuit and has a high production yield, in view of the drawbacks of the conventional technique described above.

According to this invention there is provided an accelerometer having a movable electrode which is movable according to acceleration, a fixed electrode disposed in opposition to the movable electrode, an output means for generating an output voltage which is proportional to the acceleration by measuring a gap between the movable electrode and the fixed electrode, a pulse width modulation means for generating pulses, wherein a pulse width of the pulses is modulated according to the output voltage, and a feedback means for feeding back an electrostatic force which is proportional to the pulse width of the pulses from the pulse modulation means between the movable electrode and the fixed electrode.

The object described above can be accomplished by disposing at least one fixed electrodes in such a manner as to oppose a movable electrode formed at the tip of a cantilever by miniature etching technique of silicon, letting electrostatic force act between both electrodes so that the capacitance between the movable electrode and the fixed electrode(s) reaches a predetermined value (that is, in such a manner as to restrict displacement of the movable electrode), controlling in this case the electrostatic force between both electrodes by a pulse width modulation system or providing the electrostatic force with a bias electrostatic force component so as to cause substantial linearization without using a linearization circuit, and taking out an output signal proportional to acceleration from this electrostatic force.

As first means, when electrostatic force (whose magnitude is proportional to the square of the voltage applied between both electrodes) is subjected to feedback control by a pulse width modulation system, this pulse width is accurately proportional primarily to the acceleration to be detected. As second means, relatively large bias electrostatic force is applied between the movable electrode and one of the fixed electrodes and the electrostatic force applied between the movable electrode and the other of the fixed electrodes is subjected to feedback control. In this case, the degree of the change of the voltage applied between both electrodes to generate the latter electrostatic force is substantially proportional primarily to the acceleration to be detected.

According to the two means of the invention described above, acceleration can be detected with high linearity and high level of accuracy from the electrostatic force which is subjected to feedback control in such a manner as to restrict the position of the movable electrode, without using a linearization circuit.

As stated above sensitivity and zero point of accelerometer in general have variances within certain ranges due to various factors at the time of production. Therefore, they must be somehow adjusted. The accelerometer in accordance with the present invention can be adjusted easily because it can detect the acceleration linearly. As a result, the present invention can provide a capacitance type acceleration sensor with a high production yield.

Brief Description of the Drawings

Fig. 1 shows the basic structure of an accelerometer is accordance with the present invention;

Fig. 2(b) shows a typical structure of a conventional accelerometer, and an electrical circuit thereof is shown in Fig. 2(a).

Fig. 3 is a diagram showing the relation between the displacement of a movable electrode and a capacitance in the conventional accelerometer;

Fig. 4(a) and Fig. 4(b) show variance state of initial gap dimension between electrodes;

Fig. 5 is a detailed structural view of the detection portion of the accelerometer in accordance with the present invention;

Fig. 6 is a plan view of the detection portion in Fig. 5;

Fig. 7 shows an embodiment of an electrostatic servo control method in accordance with the present invention;

Fig. 8 is a detailed explanatory view of a linear electrostatic force conversion portion in Fig. 7;

Fig. 9 shows another embodiment of the electrostatic servo control method in accordance with the present invention;

Fig. 10 shows still another embodiment of a sensing method of the accelerometer in accordance with the present invention;

Figs. 11(a) and 11(b) are detailed explanatory views of the electrostatic servo portion in accordance with the present invention;

Fig. 12 shows a structural example of the detection circuit of the accelerometer in accordance with the present invention;

Figs. 13 and 14 show the output characteristics of the accelerometer in accordance with the present invention; and

Figs. 15 and 16 shows another embodiment of the structure of the detection portion of the acceleration sensor in accordance with the present invention.

Detailed Description of the Preferred Embodiments

Hereinafter, an embodiment of the present invention will be explained with reference to Fig. 1. The detection portion of the accelerometer in accordance with the present invention consists of a movable electrode 2 formed at the tip of a silicon cantilever 1 and fixed electrodes 3 and 4 arranged to oppose the movable electrode 2. The movable electrode 2 undergoes vertical displacement between the fixed electrodes 3 and 4 depending on the magnitude and direction of the acceleration α(G) to be detected. The fixed electrodes 3, 4 and the movable electrode 2 are coupled electrically with an electrostatic servo circuit 5. Here, the movable electrode 2 is coupled through the cantilever 1. Electrostatic force is applied in a feedback control arrangement between the movable electrode 2 and the fixed electrode 3 or 4 so that the dimension of the gap between the movable electrode 2 and one of the fixed electrodes (the electrode 4 in the case of the drawing) attains a predetermined value d_o and an output signal V_{out} proportional to the acceleration α can be taken out from this electrostatic force. The electrostatic servo circuit 5 constitutes the gist of the present invention with the structure of the detection portion, though its detail will be described later.

Figs. 4(a) and 4(b) show an embodiment of the present invention which shows how to correct the variance state of the initial gap dimension between the electrodes. Solid line in Fig. 4(a) represents the state where the movable electrode 2 is at a desired position when the acceleration α acting on the accelerometer is zero. The gap dimension between the movable electrode 2 and the fixed electrode 3 in this case is assumed to be d_o. As show in Fig. 2, however, the movable electrode 2 is not always positioned at the intermediate position between the fixed electrodes 3 and 4 due to the thermal stress of the bonded portion when the glass plates 7, 8 are bonded to the silicon plate 6. For example, it is closer to the fixed electrode 3 as represented by dotted line in Fig. 4(a). For, non-uniformity of the thermal stress at the bonded portion transfers to the fixed end of the cantilever 1 and the cantilever 1 undergoes displacement either upward or downward with its own fixed end being the support point. Assuming that the dimension of the gap between the movable electrode 2 and the fixed electrode 3 is d_1, this dimension d_1 takes various values at the time of production and the conventional typical sensing method exhibits a large variance of output characteristics and invites the drop of production yield.

Accordingly, in the present invention, the movable electrode 2 is caused to undergo displacement by the electrostatic force applied between the movable electrode 2 and the fixed electrodes 3, 4 so that the movable electrode 2 comes to the intermediate position between the fixed electrodes 3 and 4 (the dimension of gap d_o) whatever value the dimension of gap d_1 between the movable electrode 2 and the fixed electrode 3 at the time of production may have, as shown in Fig. 4(a), and the dimension of gap is held at a desired value (at d_o in the drawing). Then, the output signal of the accelerometer is taken out from the electrostatic force applied between the electrodes.

The position of the movable electrode 2 when the acceleration α is zero need not always be kept at the intermediate position between the fixed electrodes 3 and 4 and the dimension of gap between the movable electrode and the fixed electrode may be kept at d_s which is closer to one of the electrodes, as shown in Fig. 4(b).

As a result, the gap dimension between the movable electrode and the fixed electrodes can be kept at d_o or d_s by the electrostatic force however the gap dimension between the electrodes may fluctuate when producing a large number of accelerometer. Accordingly, the variance of the output characteristics, that has been the problem with the typical conventional sensing method, can now be reduced.

Moreover, as will be described later, the D.C. voltage applied between the electrodes and the resulting electrostatic force have a non-linear relation.

Accordingly, the gist of the present invention resides in that when the output signal corresponding to

the acceleration is taken out from the electrostatic force applied between the electrodes while the movable electrode is kept at a desired position by the electrostatic force, the basic principle of the detection portion is provided with essential linearity. As a result, the production yield is improved and a high precision accelerometer can be provided at a reduced cost of production.

Fig. 5 shows the detailed structure of the detection portion of the accelerometer in accordance with the present invention. The movable electrode 2 serving also as a weight is formed at the tip of the cantilever 1 by etching the silicon plate 6 from both of its surfaces. Since the periphery of the movable electrode 2 is separated from the silicon plate 6 by through-hole groove 9, the movable electrode 2 responds to the acceleration to be detected and moved vertically between the fixed electrodes 3 and 4 formed on the glass plates 7 and 8 by vapor deposition or the like against the fixed end 10 of the cantilever 1 as a support point.

A sensor chip formed by bonding the glass plate 7, the silicon plate 6 and the glass plate 8 by anodic bonding or other method is fixed onto a stem 12 by use of an organic adhesive 11 (e.g. silicone rubber) having a small vertical elastic modulus (or soft adhesive). A hole 13 is bored on this metallic stem 12 and a lead 15 is hermetically sealed and fitted by a glass material 14. Since the thermal expansion coefficients of the stem 12 and glass plate 8 are mutually different, a soft silicon rubber or the like is suitable as the adhesive 11 lest the bond strain at this portion is transferred to the sensor chip above it.

Next, lead wires 17 are wire-bonded to a lead extension electrode 16 and to the lead 15 and connected electrically thereto. The electrostatic servo circuit 5 and detection portion described with reference to Fig. 1 are connected electrically through the leads 15. A cap 18 is fitted to the stem 12 in a vacuum or nitrogen atmosphere and the inside of a chamber 19 is sealed hermetically.

Fig. 6 is a view taken along A - A of the detector portion assemble, that is, a plan view. The fixed electrode 3, the movable electrode 2 and the fixed electrode 4 are wired to the electrostatic servo circuit 5 through the lead extension electrodes 22, 16, 23 and the leads 20, 15, 21, respectively. Incidentally, the hole 24 is for electrically connecting the fixed electrode 3 formed on the lower surface of the glass plate 7 to the lead extension electrode 22 and wiring is made by applying plating into the hole 24, or the like.

Fig. 7 shows the electrostatic servo control method in accordance with the present invention. When the movable electrode 2 having a mass m receives the acceleration α(G) (1G = 9.8 m/s^2), it due to the force f_1 represented by the formula (2) below with the fixed end 10 of the cantilever 1 being the center:

$f_1 = m\alpha$ (2)

Assuming that the feedback electrostatic force acting on the movable electrode 2 is f_2, then the movable electrode 2 undergoes displacement by Δd due to the force Δf:

$\Delta f = f_1 - f_2$ (3)

$$\Delta d = \frac{\Delta f}{ms^2 + rs + k} \quad \cdots\cdots (4)$$

Here, s is a Laplace constant, r is a resistance coefficient and k is a spring constant of the cantilever 1. The coefficient r is determined by the density of a fluid around the movable electrode 2, the dimension of the through-hole groove 9 and the gap between the electrodes.

Since the dimension of gap d between the movable electrode and the fixed electrode changes due to the displacement of the movable electrode 2, Δd can be detected from the electrical capacitance between the movable electrode and the fixed electrode.

In Figure 7, block 100 corresponds to the electrodes 2 to 4 and the cantilever 1 in Fig. 1 and block 200 corresponds to the electrostatic servo circuit 5 in Fig. 1.

The displacement Δd of the movable electrode 2 is converted to a voltage V^* by a switched capacitor circuit 25 having a gain K_1 and is compared with a reference voltage V_{ref}. As will be described later, the switched capacitor circuit 25 applies a rectangular voltage wave train between the electrodes and the dimension d of gap can be detected directly from the capacitance between the electrodes. The electrostatic servo circuit in the drawing is subjected to feedback controls so as to satisfy the formula

$V_{ref} - V^* = 0$ (5)

and the gap between the movable electrode 2 and one of the fixed electrodes is kept at a constant value. As shown in Fig. 4(a) and Fig. 4(b), the dimension of gap d_o or d_s between the movable electrode 2 and the fixed electrode 4 can be kept always at a desired value irrespective of the magnitude and direction of the acceleration α. At the same time, the problems resulting from the variance of the gap dimension between the movable electrode and the fixed electrode at the time of production can be overcome and a high performance accelerometer can be provided at a low cost of production.

The electrostatic servo mechanism is subjected to the feedback control by the voltage applied between the movable electrode and the fixed electrode in such a manner as to satisfy the formula (5) and the output signal V_{out} which is accurately proportional primarily to the acceleration α to be detected is taken out through an integrator 26.

The electrostatic force f_2 is feedback-controlled linearly by a linear electrostatic force conversion portion 27 with respect to the acceleration α to be detected on the basis of the output signal V_{out}. As will be explained in detail with reference to the next drawing, the electrostatic force f_2 that operates in such a manner as to attract the movable electrode 2 to the fixed electrode 4 is controlled essentially linearly without the need of the linearization circuit.

The linear electrostatic force conversion portion 27 consists of a pulse width modulator 28 having a gain K_2 and an electrostatic force conversion portion 29 having a gain K_3.

Next, the detail of the linear electrostatic force conversion portion 27 will be described with reference to Fig. 8.

The output signal V_{out} is modulated to a pulse train having a period T by the pulse width modulator 28 and its pulse width becomes a + a_o. Here, a is a variable portion of the pulse width which is varied in proportional to the acceleration α, and a_o is a base portion of the pulse width when the acceleration α is zero. The period T of the pulse train is decided so that the frequency of the pulse train becomes sufficiently greater than the inherent frequency of the detection portion consisting of the cantilever 1 and the movable electrode 2. The inherent frequency of the detection portion produced tentatively is 1.5(KHz) and in this case, the period T is set to 50(μs). Incidentally, the voltage peak value E of the pulse train is always constant.

The proportional gain K_3 of the electrostatic force conversion portion 29 is determined physically and is given as follows when the movable electrode 2 is kept at the ground level and the pulse train described above is applied to the fixed electrode 4:

$$K_3 = \frac{\varepsilon_o s E^2}{2 d_s{}^2} \quad \cdots\cdots (6)$$

The electrostatic force f_2 attracting the movable electrode 2 towards the fixed electrode 4 is given as follows:

$$f_2 = \frac{(a+a_o)\, \varepsilon_o s E^2}{2 T d_s{}^2} \quad \cdots\cdots (7)$$

What is important in the formula (7) above is that the voltage peak value E of the pulse train applied between the movable electrode 2 and the fixed electrode 4, its period T and the gap dimension d_s between the electrodes are constant and the electrostatic force f_2 is primarily proportional to (a + a_o) obtained by the pulse width modulation of the output signal V_{out} and is subjected to feedback control to a completely linear from without the need of the lenearization circuit.

Incidentally, the base portion a_o of the pulse width generates the electrostatic force for setting the gap dimension between the movable electrode 2 and the fixed electrode 4 to d_s under the state where the acceleration is zero. In other words, the smaller the gap dimension d between the movable electrode 2 and the fixed electrode 4 at the time of production, the smaller becomes a_o and the greater the d value, the greater becomes the a_o value.

The variable portion a of the pulse width changes the electrostatic force f_2 in proportion to the acceleration α to be detected and is in agreement with the polarity of the acceleration α as expressed by the following formula:

when $\alpha \gtreqless 0$, $a \gtreqless 0$ (8)

In other words, if the acceleration in the direction from the side of the fixed electrode 4 towards the side of the fixed electrode 3 is defined as $\alpha > 0$, the width of the pulse train increases when $\alpha > 0$ as represented by dotted line in the drawing and decreases when $\alpha < 0$. The proportion of the increase or decrease of the pulse train changes linearly with respect to the acceleration α (accurately proportional primarily). As a result, the following formula of output signal V_{out} is established:

$V_{out} \propto Km\alpha$ (9)
where K is a proportional constant.

As expressed by the formula (9), the acceleration α can be detected with high linearity without being affected by the variance of the gap dimension between the movable electrode 2 and the fixed electrode 4 occurring at the time of production and by the influence of the spring constant k of the cantilever 1.

Furthermore, the output signal V_{out} may be taken out from the output side of the pulse width modulator 28.

Incidentally, the switched capacitor circuit 25 detects the capacitance between the movable electrode 2 and the fixed electrode 4 by utilizing the pulse train for generating the electrostatic force that is applied between both electrodes 2 and 4. Though a detailed example of the detection circuit is described later, the capacitance C_s can be detected from the following formula by charging the charge Q in the capacitance C_s formed between both electrodes at the instant when the voltage E having a constant peak value is applied between both electrodes, and by transferring this charge Q to a known capacitance C_{ref} at the instant when the voltage E becomes zero:
$Q = C_sE$ (10)
$Q = C_{ref} \cdot E^*$ (11)
From the formulas (10) and (11),

$$C_s = C_{ref}\frac{E^*}{E} \qquad \cdots\cdots (12)$$

Therefore, the capacitance C_s between both electrodes can be detected by measuring the voltage E^* occurring in the known capacitance C_{ref}. If the capacitance C_s is defined as follows,

$$C_s = \frac{\varepsilon_o s}{d_s} \qquad \cdots\cdots (13)$$

the electrostatic servo mechanism show in Fig. 7 operates as expressed by the formula (5) and the capacitance between both electrodes is controlled to C_s. Furthermore, the gap between the movable electrode 2 and the fixed electrode 4 is kept at a desired predetermined value d_s without depending on the magnitude and direction of the acceleration α to be detected.

In the system shown in Figs 7 and 8, the detection of the capacitance and the generation of the electrostatic force are made between the same electrodes and the fixed electrode opposing the movable electrode 2 is only one. Therefore, the structure of the detection portion is extremely simple.

When the gap dimension d between the movable electrode 2 and the fixed electrode 4 is smaller than the desired set value d_s, detection of the acceleration α becomes difficult in accordance with the method shown in Fig. 4(b).

The detection system in this case is shown in Fig. 9. In this drawing, D.C. electrostatic force f_{bias} is added bias-wise to the method of Fig. 7. The movable electrode 2 can be moved in the direction of the fixed electrode 3 by applying f_{bias} between the fixed electrode 3 and the movable electrode 2. As a result, detection of the acceleration α can be made even when the gap between the movable electrode 2 and the fixed electrode 4 at the time of production is smaller than d_s. As shown in Fig. 4(a), the acceleration α can also be detected by holding the position of the movable electrode 2 at the intermediate position between the fixed electrode 3 and 4 by the electrostatic force in the feedback control arrangement as shown in Fig. 4(a).

Fig. 10 shows another embodiment of the sensing system of the acceleration sensor in accordance with the present invention. This system measures the gap between the movable electrode 2 and one of the fixed electrodes, makes feedback control by the electrostatic force applied between the movable electrode 2 and the other of the fixed electrodes so that the gap dimension attain a predetermined value irrespective of the direction and magnitude of the acceleration α, and takes out the output signal corresponding to the acceleration α from this electrostatic force. In other words, the capacitance between the movable electrode 2 and one of the fixed electrode is measured (or in other words, the gap between the electrodes is

measured) by applying the electrostatic force f_{bias} of the pulse train having a predetermined period between them and the movable electrode 2 is caused to displace towards one of the fixed electrodes. The electrostatic force f_2 which causes displacement of the movable electrode 2 towards the other of the fixed electrodes is applied in the feedback control arrangement between the movable electrode 2 and the other of the fixed electrodes through a D.C. electrostatic force conversion portion 30 having a gain K_4 from the output signal V_{out}. As a result, the movable electrode 2 can be fed back and controlled to a desired position between the fixed electrodes 3 and 4. Since the following formula is established, the acceleration α can be detected from the electrostatic force f_2 applied between the movable electrode 2 and the other of the fixed electrodes:

$V_{out} \propto m\alpha/K_4$ (14)

The electrostatic servo system of this drawing will be described in detail with reference to Figs. 11(a) and 11(b). The item f_{bias} to be applied between the movable electrode 2 and the one of the fixed electrodes in Fig. 11(a) is a pulse train having period T and a voltage peak value E_b (with E_b being a constant value). The reason why the f_{bias} item is the pulse train is to measure the capacitance C_s between the electrodes by the switched capacitor having the gain k_1 using the pulse train shown in Fig. 8. If the frequency of the pulse train is sufficiently higher than the inherent frequency of the movable electrode system formed at the tip of the cantilever 1, the pulse-like electrostatic force f_{bias} acts substantially as the D.C.-like electrostatic force on the movable electrode 2. In the pulse train, the zone where the voltage peak value is E_b is defined as a and the zone where it is zero, as b. When a $\gg$ b, a sufficiently large electrostatic force f_{bias} can be applied between the movable electrode 2 and one of the fixed electrodes by setting the voltage peak value E_b to a large value.

Next, the item f_2 of the feedback electrostatic force shows in Fig. 11(b) will be explained. The following formula is established when the acceleration α is zero:

$f_2 = f'_{bias} + f_s$ (15)

Here, f'_{bias} is the value obtained by substantially smoothing the pulse-like electrostatic force f_{bias} to the D.C. component and f_s is the electrostatic force necessary for setting the movable electrode 2 between the fixed electrodes 3 and 4. Incidentally, f_s takes a positive or negative value depending on the relation of the positions between the position of the movable electrode 2 at the time of production and the position at which it is to be held. The drawing shows the case where it is positive. If the acceleration to be detected is α, the feedback electrostatic force f_2 increases when $\alpha > 0$ and decreases when $\alpha < 0$.

As shown in the drawing, the electrostatic force f_2 acts D.C.-wise unlike in the pulse width modulation system shown in Fig. 7. Since linearity of the output signal V_{out} becomes the problem in this case, its counter-measure will be explained. The gain K_4 is given by the following formula and is proportional to V_{out}:

$$K_4 = \frac{\varepsilon_0 s V_{out}}{2 d_s^2} \qquad \cdots\cdots (16)$$

As a result, the output signal V_{out} has non-linearity with respect to the acceleration α as can be understood from the formulas (14) and (16).

Accordingly, the output signal V_{out} is divided to a constant component V and a change component ΔV and is defined as follows:

$V_{our} = V + \Delta V$ (17)

Here, ΔV and V are those components which are responsive and are not responsive to the acceleration α to be detected, respectively. If the voltage peak value E_b of the pulse train of the electrostatic force f_{bias} item is set to a large value, $f_{bias} \gg f_1$. Therefore, since $f_2 \gg f_1$, $V \gg \Delta V$.

In this case, the gain K_4 is approximately expressed as follows and can be regarded as a substantially constant value:

$$K_4 = \frac{\varepsilon_0 s V}{2 d_s^2} \qquad \cdots\cdots (18)$$

The change component ΔV of the output signal corresponding to the acceleration α is given as follows:

$\Delta V \propto m\alpha/K_4$ (19)

and ΔV is substantially proportional to the acceleration α to be detected. Therefore, the acceleration α can be detected highly accurately with substantially high linearity without requiring any linearization circuit by separating only the change component ΔV from V_{out}. Though Fig. 10 does not show this portion, the change component ΔV proportional to the acceleration can be detected easily by subtracting the predetermined constant component V from V_{out} by use of a differential amplifier.

Incidentally, when the constant component V is 5 V and the change component ΔV is 0.1 V, linearity at the time of detection of the acceleration α is about 1%. If the voltage value V of the steady component is set to a greater value, linearity can be further improved.

Next, Fig. 12 shows a structural example of the detection circuit of the accelerometer in accordance with the present invention. The drawing shows the circuit which detects the acceleration α by use of the electrostatic servo control method shown in Fig. 7 and the circuit added f_{bias} shown in Fig. 9 is not comprised in the circuit shown in Fig. 12. This circuit consists of a power source protection circuit portion 31, a constant voltage circuit portion 32, a switched capacitor circuit portion 33, an integrator 34, a pulse width modulator 35 and an output regulation circuit portion 36. In the drawing, V_B represents a voltage of a battery of a vehicle.

While the switch 37 is ON, a current is supplied from a resistor 38 between the movable electrode 2 and one of the fixed electrode 4 at the detection portion of the accelerometer to charge the charge in the capacitance C_s 39. Next, at the instant when the supply of the current is stopped, the switch 37 is turned OFF and the charge of the capacitance C_s 39 is transferred to the known capacitance C_{ref} 40. As a result, the value of the capacitance C_s between the movable electrode 2 and the fixed electrode 4 is detected in accordance with the formula (12).

The electrostatic force applied between the movable electrode 2 and the fixed electrode 4 through the pulse width modulator 35 is feedback-controlled so that the capacitance C_s attains a predetermined constant value. The output signal V_{out} accurately proportional to the acceleration is taken out from this pulse width through the output regulation circuit portion 36.

Furthermore, the embodiments of the present invention stated above showed the case which measure only one gap between the movable electrode and one of the two fixed electrode. But, as shown in Fig. 1, the both of the gaps between the movable electrode 2 and the fixed electrodes 3 and 4. In this case, the pulse width modulator 35 is modulated according to a deviation of the two gaps, and the output of the pulse width modulator 35 is fed back between the movable electrode and at least one of the two fixed electrodes.

Next, Figs. 13 and 14 show the examples of the output characteristics of the prototype accelerometer measured by use of this circuit. Fig. 13 shows static characteristics and the acceleration of form 0 to ±1(G) can be detected with high linearity. Fig. 14 shows dynamic characteristics and detection sensitivity is substantially constant between the frequency of 0 and 50(Hz).

As describe above, the accelerometer in accordance with the present invention is suitable as a key sensor for controlling a car body.

Next, another embodiment of the detection structure capable of detecting the acceleration with a high level of accuracy in accordance with the electrostatic servo method of the present invention will be described.

Needless to say, the movable electrode may be supported not only by the cantilever structure by also by a plurality of beams such as double-end beam structures.

Fig. 15 and 16 show another embodiment of the structure of the detection portion in accordance with the present invention. Fig. 15 shows a system which measures the position of the movable electrode 2 by optical position sensing elements 41, 42 and holds the movable electrode 2 at a desired position between the fixed electrodes 3 and 4 by the electrostatic servo circuit 5. At this time the acceleration is detected from the electrostatic force applied in the feedback control arrangement between the movable electrode 2 and the fixed electrodes 3, 4 from the electrostatic servo circuit 5. The difference of this system from those shown in Figs. 7, 9 and 10 is that the position measurement of the movable electrode is made by use of the optical position sensing elements 41, 42 in place of the switched capacitor circuit 25.

Fig. 16 shows the system which measures the position of the movable electrode 2 by a semiconductor strain gauge 43 formed on the cantilever 1, and the rest of operations are the same as those of Fig. 15.

In accordance with the present invention, the electrostatic servo mechanism can be operated substantially linearly with respect to the acceleration to be detected by electrostatic pulse width modulation or electrostatic bias method while the movable electrode is held electrostatic servo-wise at a desired position. Accordingly, the acceleration can be detected with a high level of accuracy without the need for a linearization compensation circuit.

Since the basic principle of the detection portion is substantially linear, the variance of the output characteristics due to various factors during production can be reduced and the production yield can be

improved.

As a result, the present invention can provide a capacitance type accelerometer which satisfies all the requirements of high sensitivity, high impact resistance and high performance at a low cost of production.

Claims

1. An accelerometer having,
a movable electrode which is movable according to acceleration,
a fixed electrode disposed in opposition to the movable electrode,
an output means for generating an output voltage which is proportional to the acceleration by measuring a gap between the movable electrode and the fixed electrode,
a pulse width modulation means for generating pulses, wherein a pulse width of the pulses is modulated according to the output voltage, and
a feedback means for feeding back an electrostatic force which is proportional to the pulse width of the pulses from the pulse modulation means between the movable electrode and the fixed electrode.

2. An accelerometer as defined claim 1 further characterized by,
said gap being measured by detecting a capacitance between the movable electrode and the fixed electrode.

3. An accelerometer as defined claim 1 further characterized by,
said gap being optically measured by a photodetector.

4. An accelerometer as defined claim 1 further characterized by,
said gap being measured by a semiconductor strain gauge.

5. An accelerometer as defined claim 1 further characterized by, means for determining said output voltage as a deviation between a signal according to the gap and a predetermined value.

6. An accelerometer as defined claim 1 further having,
a bias circuit for adding a bias of D.C. voltage between the movable electrode and the fixed electrode.

7. An accelerometer having,
a movable electrode which is movable according to acceleration,
a fixed electrode disposed in opposition to the movable electrode,
an output means for generating an output voltage which is proportional to a deviation between a gap and a predetermined value as the acceleration, wherein the gap is measured between the movable electrode and the fixed electrode, and
a feedback means for feeding back an electrostatic force in proportion to the gap between the movable electrode and the fixed electrode.

8. An accelerometer as defined claim 7 further characterized by,
said gap being measured by detecting a capacitance between the movable electrode and the fixed electrode.

9. An accelerometer as defined claim 7 further characterized by,
said gap being optically measured by a photodetector.

10. An accelerometer as defined claim 7 further characterized by,
said gap being measured by a semiconductor strain gauge.

11. An accelerometer as defined claim 7 further having,
a bias circuit for adding a bias of pulse train having a predetermined period between the movable electrode and the fixed electrode.

12. An accelerometer having,
a movable electrode which is movable according to acceleration,
a fixed electrode disposed in opposition to the movable electrode,
a gap measuring means for measuring a gap between the movable electrode and the fixed electrode,
a pulse width modulation means for generating pulses, wherein a pulse width of the pulses is modulated according to a deviation between the gap and a predetermined value,
a feedback means for feeding back an electrostatic force which is proportional to the pulse width of the pulses from the pulse modulation means between the movable electrode and the fixed electrode, and
an output means for generating an output voltage which is proportional to the pulse width as the acceleration.

13. An accelerometer as defined claim 12 further characterized by,
said gap being measured by detecting a capacitance between the movable electrode and the fixed electrode.

14. An accelerometer as defined claim 12 further characterized by,
said gap being optically measured by a photodetector.

15. An accelerometer as defined claim 12 further characterized by,
said gap being measured by a semiconductor strain gauge.

16. An accelerometer as defined claim 12 further having,
a bias circuit for adding a bias of D.C. voltage between the movable electrode and the fixed electrode.

17. An accelerometer having,
a movable electrode which is movable according to an acceleration,
first fixed electrode facing to one side of the movable electrode,
second fixed electrode facing to the other side of the movable electrode,
a gap measuring means for measuring two gaps between the movable electrode and the first and the second fixed electrodes,
a pulse modulation means for generating pulses, wherein a pulse width of the pulses is modulated according to an deviation of two gaps,
a feedback means for feeding an electrostatic force which is proportional to the pulse width of the pulses from the pulse modulation means between the movable electrode and at least one of the first and the second fixed electrodes, and
an output means for generating an output voltage which is propcrtional to the acceleration by measuring a gap between the movable electrode and one of the first and the second fixed electrodes.

18. An accelerometer as defined claim 17 further characterized by,
said gap in the output means being measured by detecting a capacitance between the movable electrode and one of the first fixed electrode and the second fixed electrodes.

FIG. 1

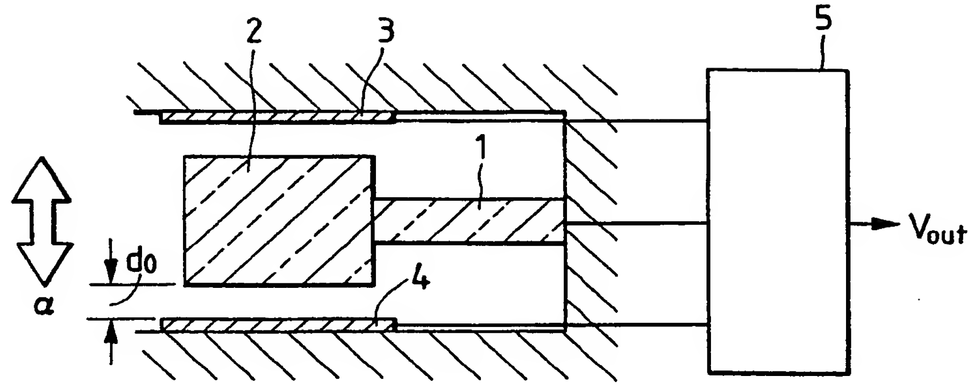


FIG. 2(a)

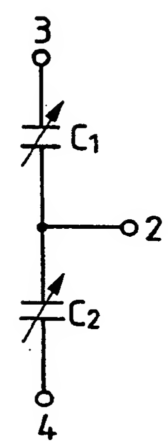


FIG. 2(b)

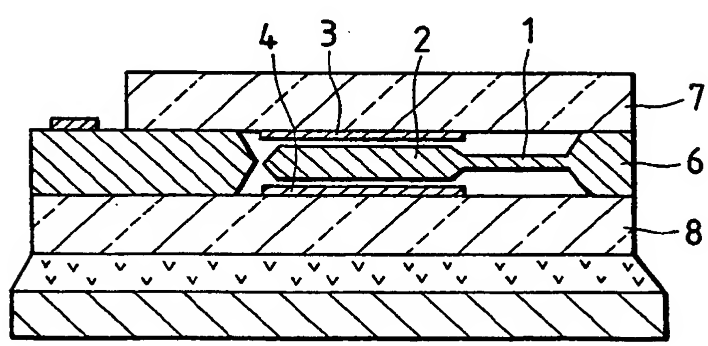


FIG. 3

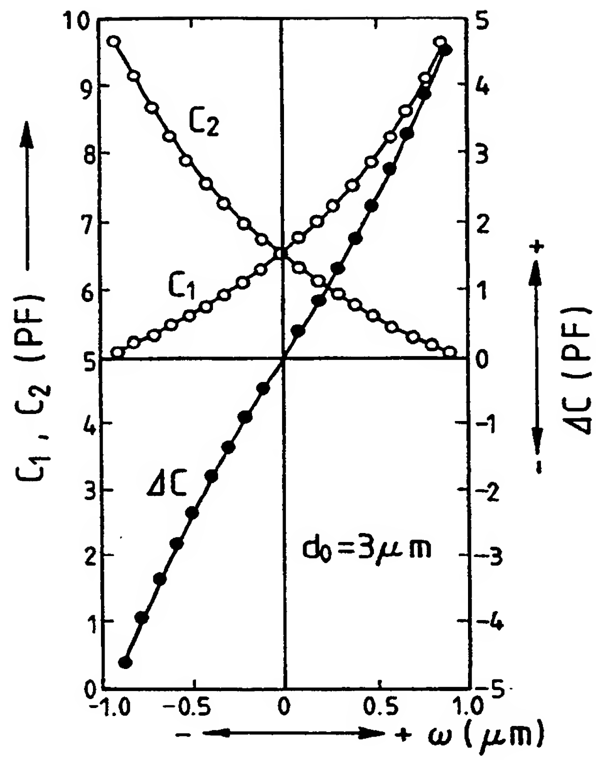


FIG. 4(a)

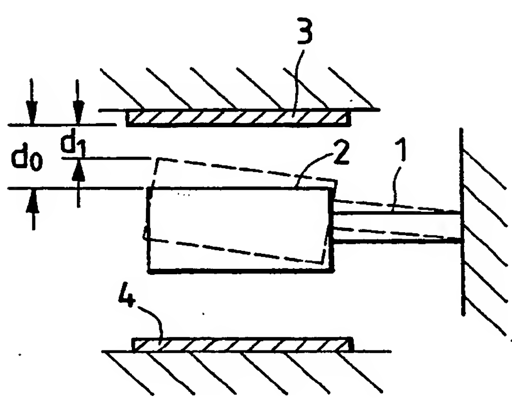


FIG. 4(b)

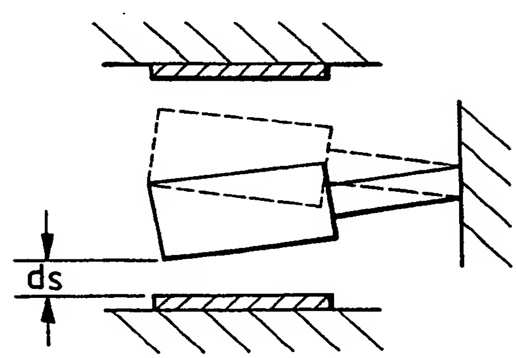


FIG. 5

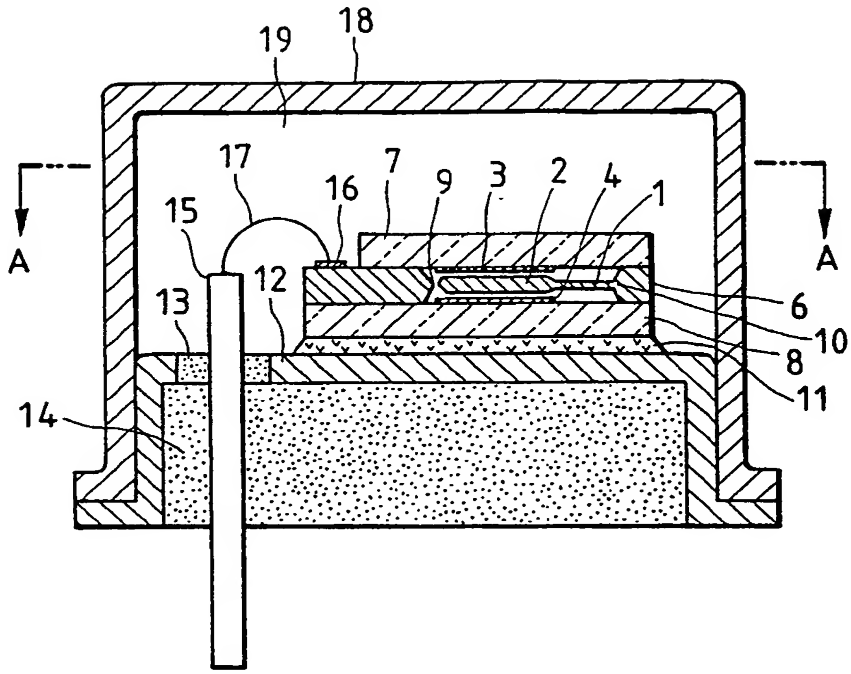

18
19
17
16
7
9
3
2
4
1
15
A
A
12
6
10
13
8
11
14

FIG. 6

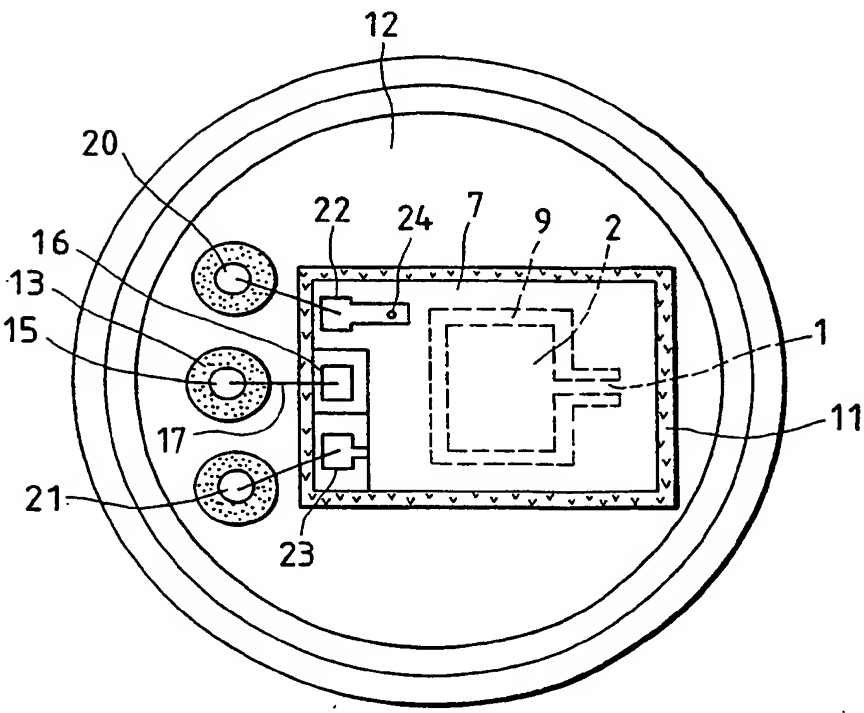

12
20
22
24
7
9
2
16
13
1
15
11
17
21
23

FIG. 7

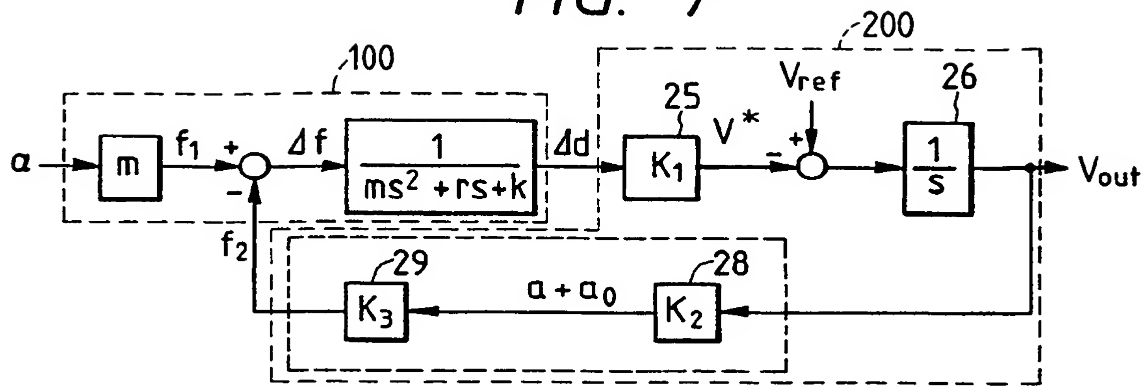


FIG. 8

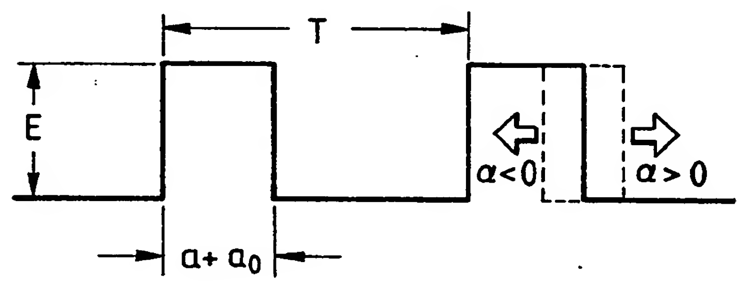


FIG. 9

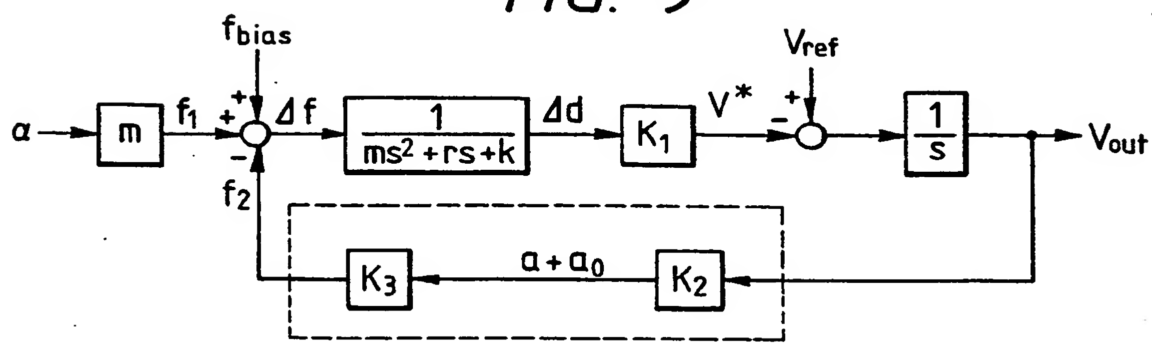


FIG. 10

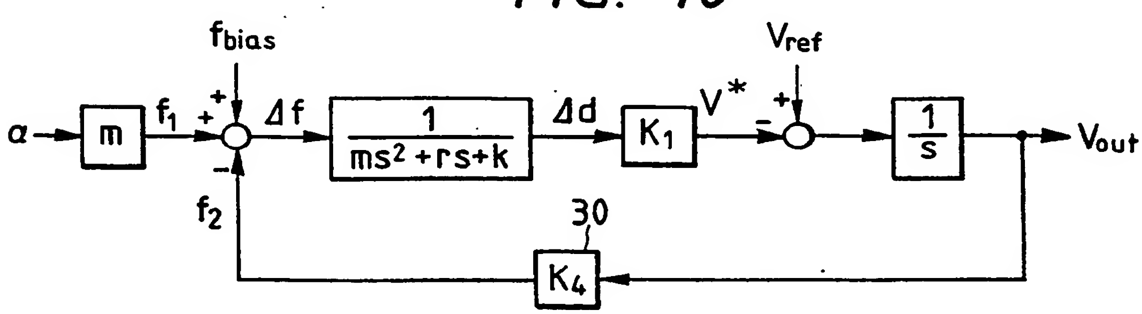


FIG. 11(a)

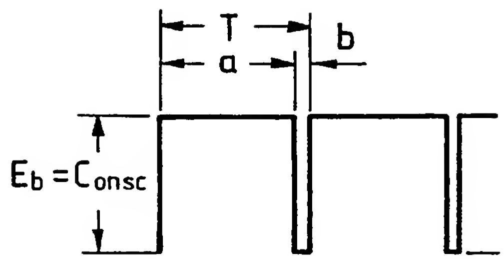


FIG. 11(b)

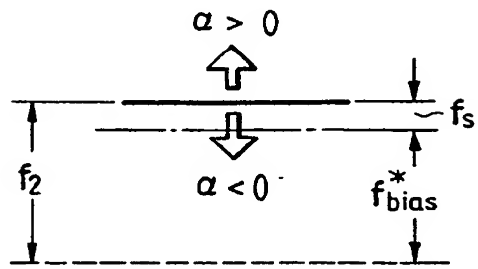


FIG. 12

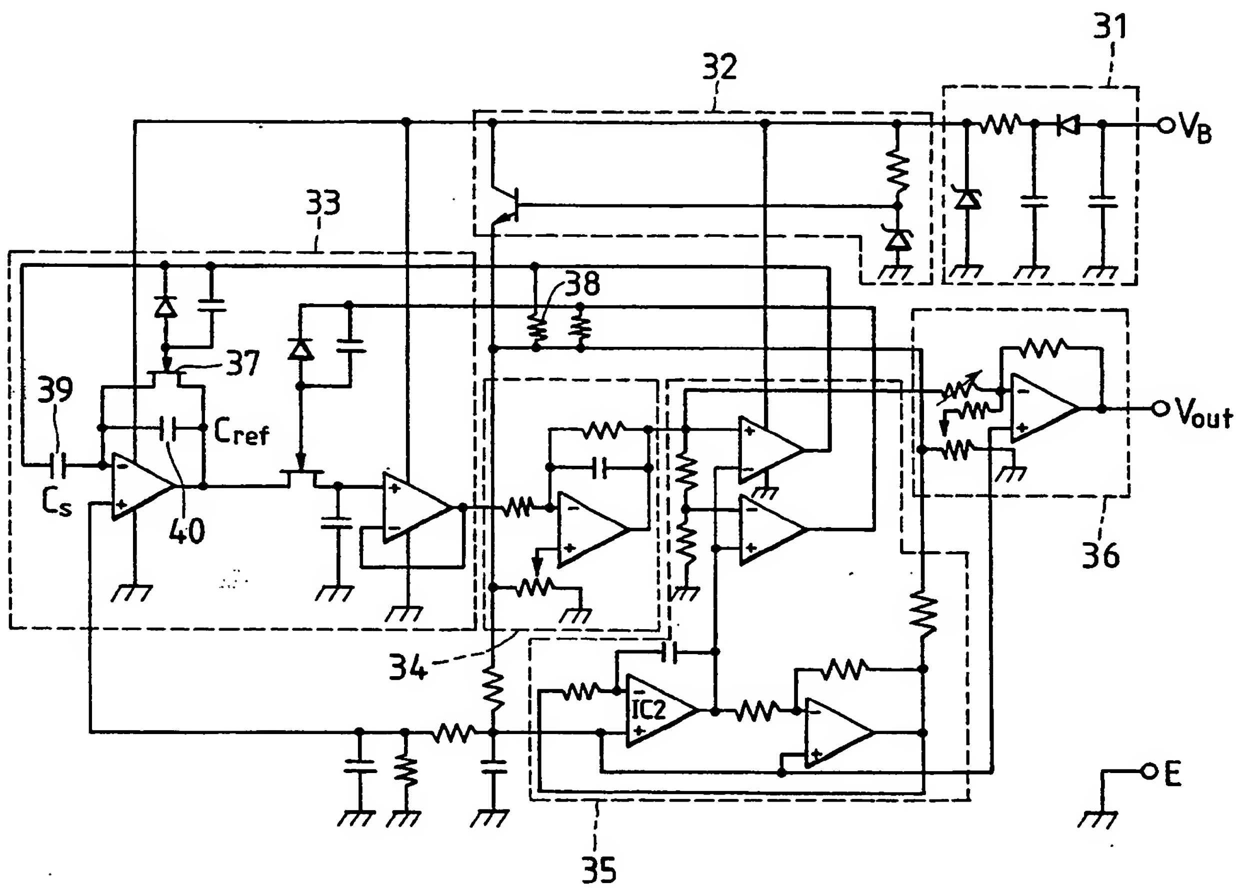


FIG. 13

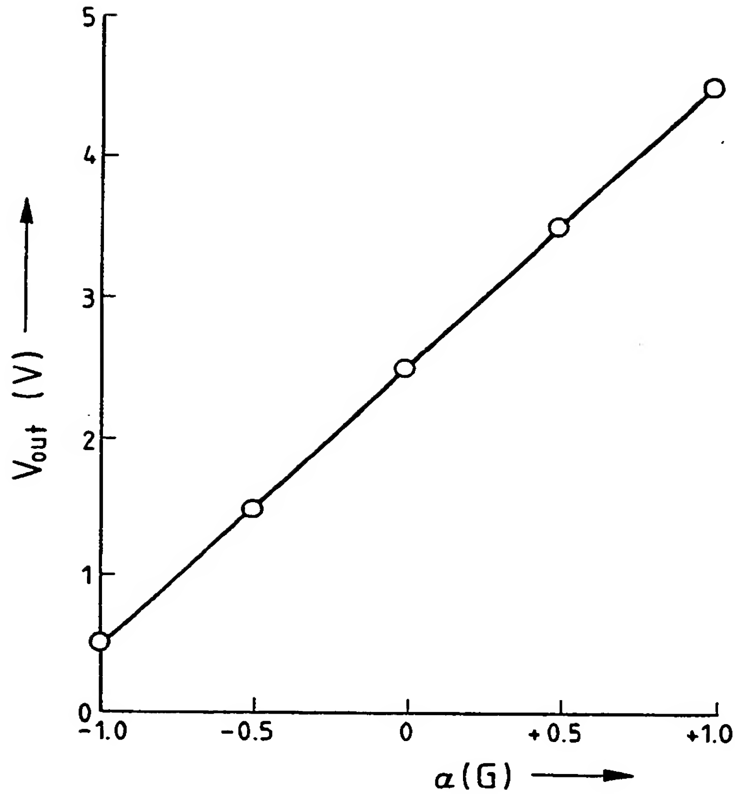

5
4
3
2
1
0
V_{out} (V)
-1.0
-0.5
0
+0.5
+1.0
α (G)

FIG. 14

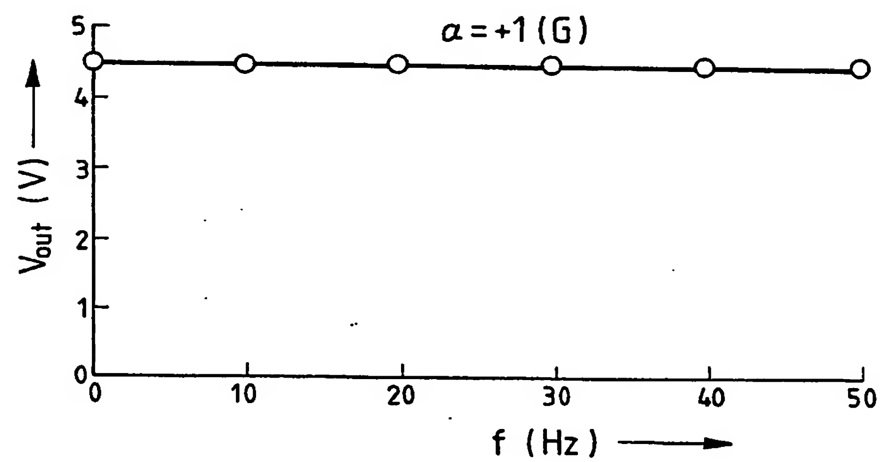

α = +1 (G)
5
4
3
2
1
0
V_{out} (V)
0
10
20
30
40
50
f (Hz)

FIG. 15

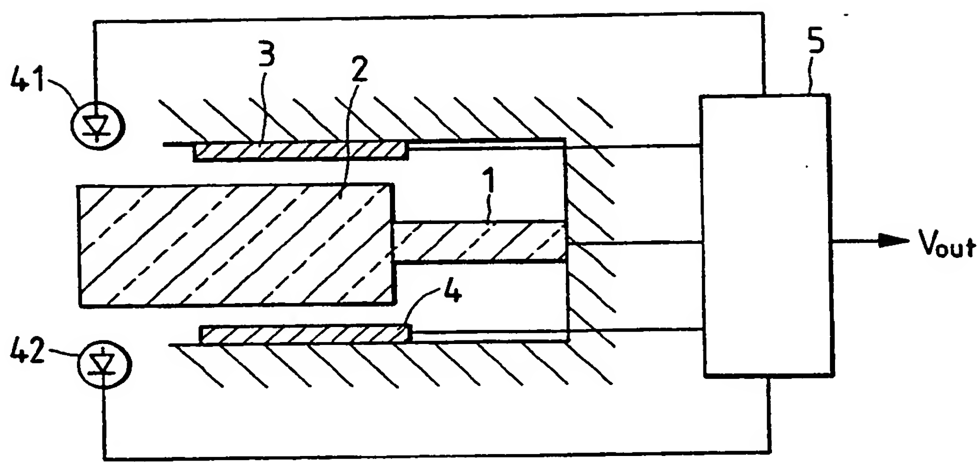
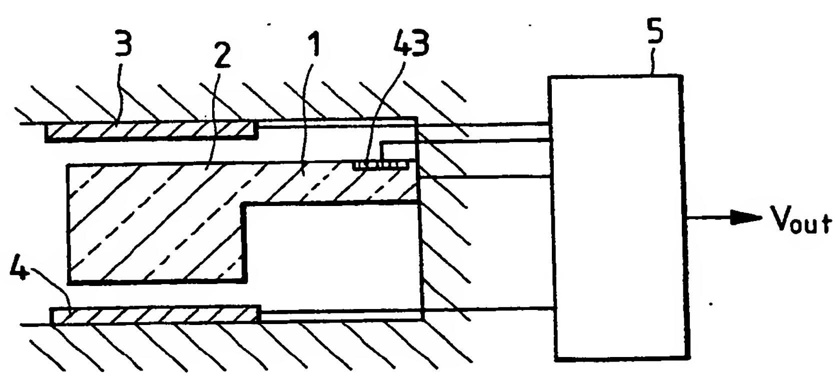


FIG. 16



European Patent Office

EUROPEAN SEARCH REPORT

Application Number

EP 89 30 3120

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (Int. Cl.4)
A	GB-A-2 096 326 (MINISTRY OF DEFENCE) * Page 1, lines 3-7,17-24,62-65,98-108; page 2, lines 8-48,58-64,107-111; figures 1,5 *	1-3,6-9,12,13,17,18	G 01 P 15/13 G 01 P 15/125
A	US-A-4 336 718 (WASHBURN) * Column 1, lines 5-8,19-60; column 2, lines 6-57; column 2, line 62 - column 3, line 4; figure 1 *	1,2,5-8,11-13,16-18	
			TECHNICAL FIELDS SEARCHED (Int. Cl.4)
			G 01 P

The present search report has been drawn up for all claims

Place of search	Date of completion of the search	Examiner
THE HAGUE	25-07-1989	ROBINSON M.A.

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons

& : member of the same patent family, corresponding document